Physics

Nuclear Fission inside Astrophysical Plasmas

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Physical and Life Sciences

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The role of fission in the nucleosynthesis of heavy elements

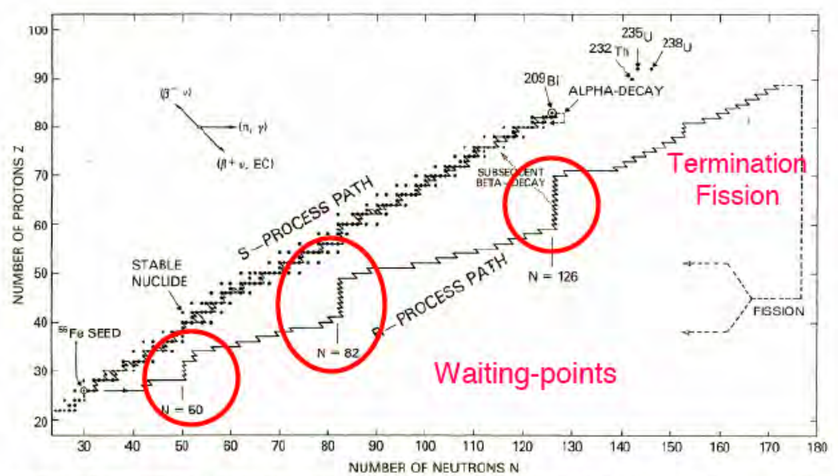

FIGURE 9.13. Neutron-capture paths for the s-process and the r-process are shown in the (N, Z)-plane. Both paths start with the iron-peak nuclei as seeds (mainly ^{56}Fe). The s-process follows a path along the stability line and terminates finally above ^{209}Bi via α-decay (Cla67). The r-process drives the nuclear matter far to the neutron-rich side of the stability line, and the neutron capture flows upward in the (N, Z)-plane until β-delayed fission and neutron-induced fission occur (Thi83). The r-process path shown was computed (See65) for the conditions $T_9 = 1.0$ and $N_n = 10^{24}$ neutrons cm^{-3}.

Fission limits heaviest element production & re-seeds r process

However

- **Virtually all fission calculations ignore HD plasma environment:**
- **Very high electron densities (for neutron stars: $n_e \sim 10^{35}$-10^{38} cm^{-3})**
  - ⇒ screened Coulomb
  - ⇒ modified fission
- **Very high particle fluence**
  - ⇒ fission from excited states

No calculation has ever followed a fissioning nucleus to scission inside HD plasma!

Neutron stars and the r process

PRL **111,** 242502 (2013) PHYSICAL REVIEW LETTERS week ending 13 DECEMBER 2013

New Fission Fragment Distributions and *r*-Process Origin of the Rare-Earth Elements

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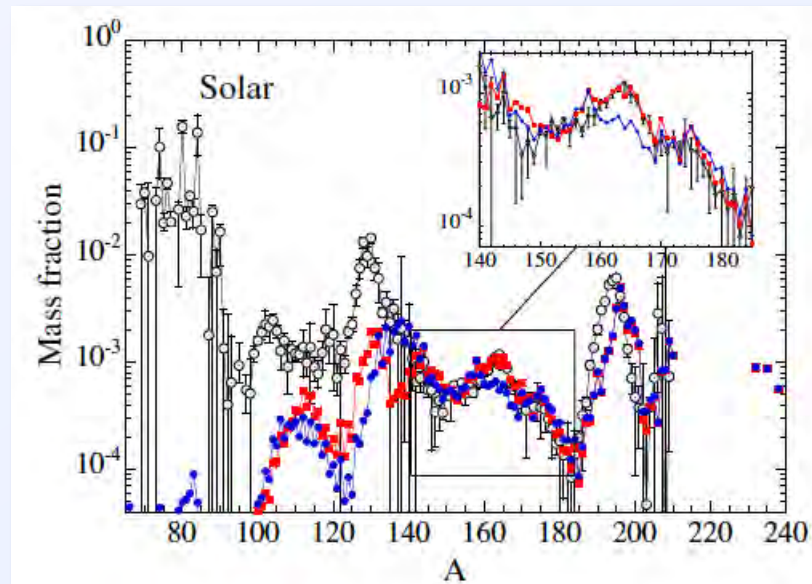
NS merger simulations

+

Fission-fragment distribution from scission-point model ("Wilkins" + HFB)

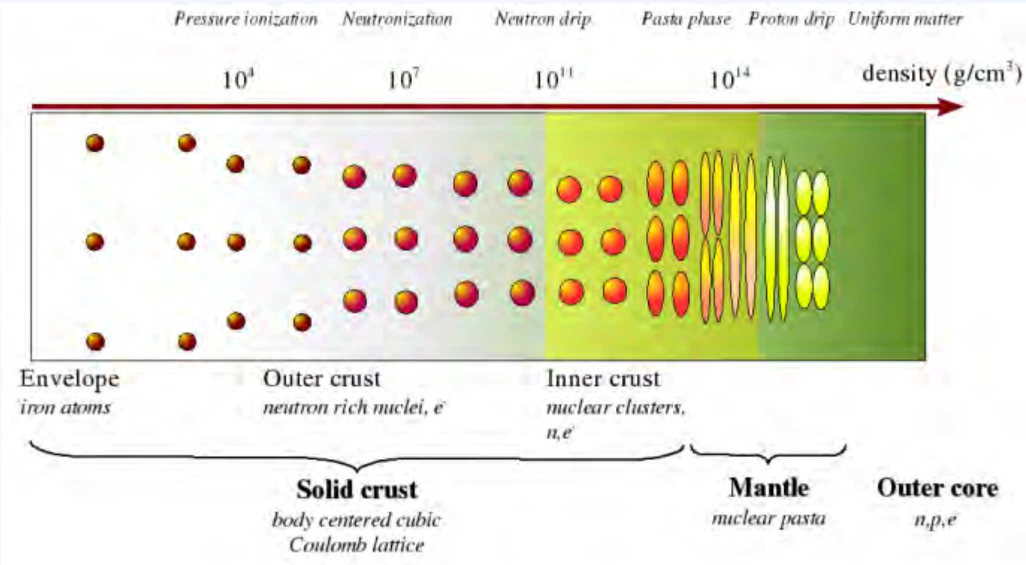
+

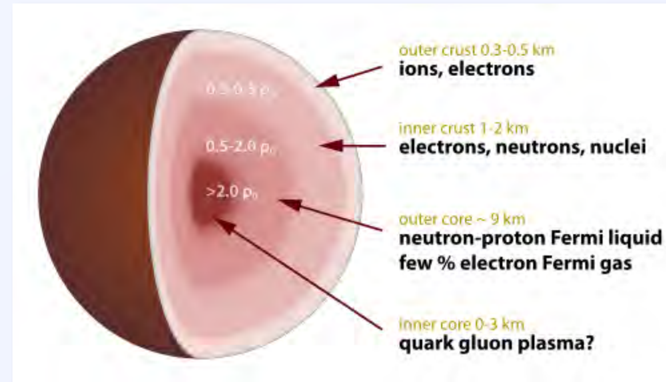
Nucleosynthesis calculations with multiple fission recycling events



Intriguing results, but fission model has: no Coulomb screening and no dynamics!

Nuclear physics inside neutron stars





Nuclei + <u>high</u> e⁻ density in the crust of neutron stars

Remember the Bohr model, for an actinide:

$$r_{e^-} = \frac{a_0}{Z} \approx 75 \times \text{nuclear radius}$$

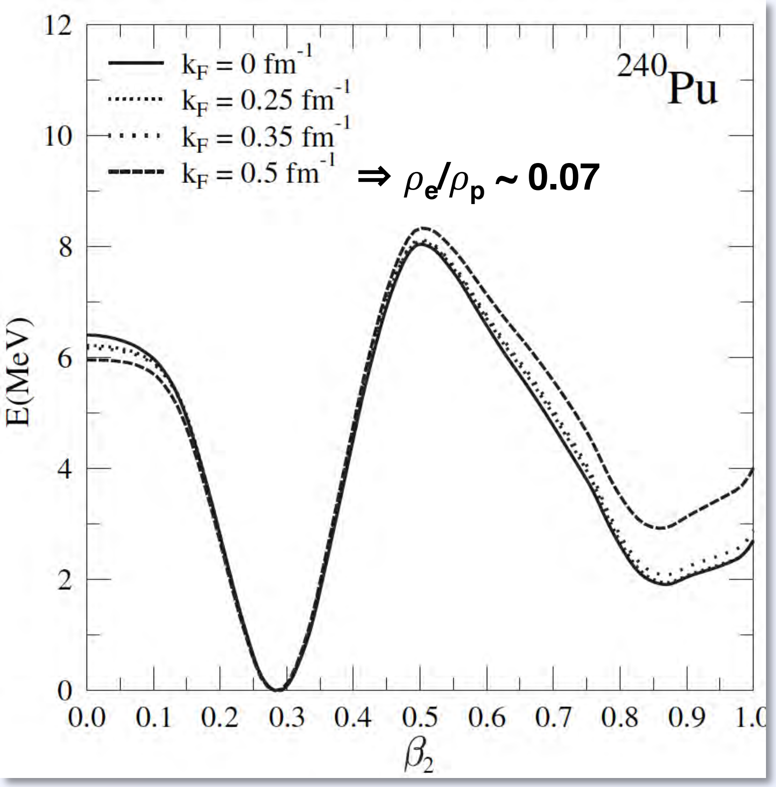
On earth, nucleons and electrons live (mostly) separate lives

In a neutron star, e⁻ are well inside the nuclei!

- **⇒ Coulomb repulsion altered (e⁻ screen the proton charge)**
- **⇒ Fission is fundamentally modified**

Nuclear fission at high electron densities

Only two papers on the topic, most extensive treatment is by Bürvenich et al. PRC 76, 034310 (2007):



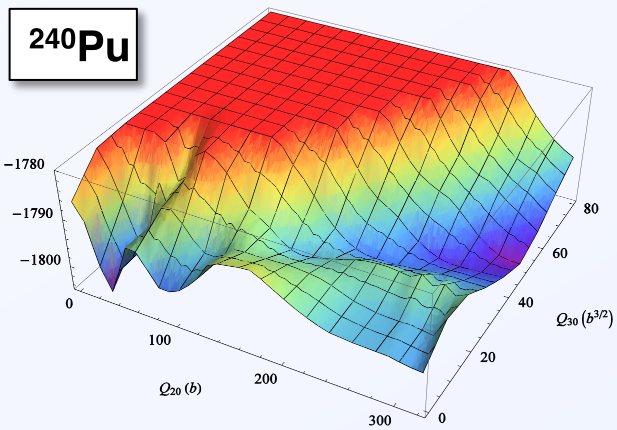
- Intriguing results!
- Barriers are noticeably affected even in the outer crust of NS!
- But calculations stop right after 1st barrier
- Scission is near $\beta_2 \sim 3.7$
- Also, what about fragment properties: yields, energies, spectra…

A microscopic approach to “normal” fission

- Starting point is effective interaction between nucleons
  - Finite-range, fit a-priori, to very few nuclear data
- Simplest treatment of nucleon correlations is Mean Field
  - Valid if nearby excitations $\gg$ residual interaction (e.g., magic nuclei)
  - Otherwise true wave function mixes with nearby excitations
- Introduce correlations into Hamiltonian via successive improvements
  1. $H_{true} \approx H_{MF}$ (Hartree-Fock)
  2. $H_{true} \approx H_{MF} + V_{pair}$ (Hartree-Fock-Bogoliubov)
  3. $H_{true} \approx H_{MF} + V_{pair} + V_{coll}$ (Generator-coordinate method)
  4. $H_{true} \approx H_{MF} + V_{pair} + V_{coll} + V_{coll\text{-}intr}$ (GCM + qp excitations)
  5. …

Tractable approach to a microscopic treatment of fission

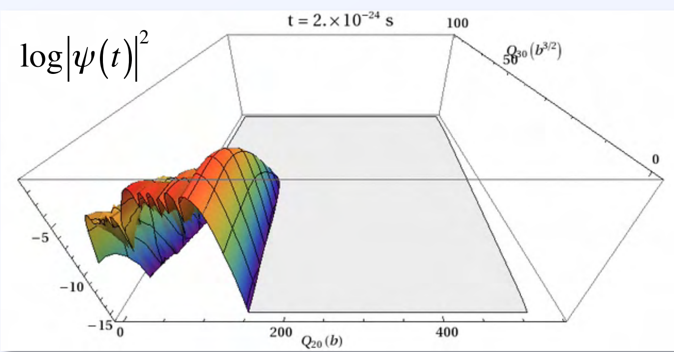
Building collective motion from single particles



- **Each point on map is a single configuration: HFB ⇒ Φ(q)**
- **The nucleus explores many such configurations ⇒ form linear superposition of Φ(q):** $\left|\Psi(t)\right\rangle = \int dq\, f(q,t) \left|\Phi(q)\right\rangle$
- **Use variational procedure to determine the weights *f*(*q,t*):** $\delta E = \delta \left\langle \Psi \middle| H \middle| \Psi \right\rangle / \left\langle \Psi \middle| \Psi \right\rangle = 0$

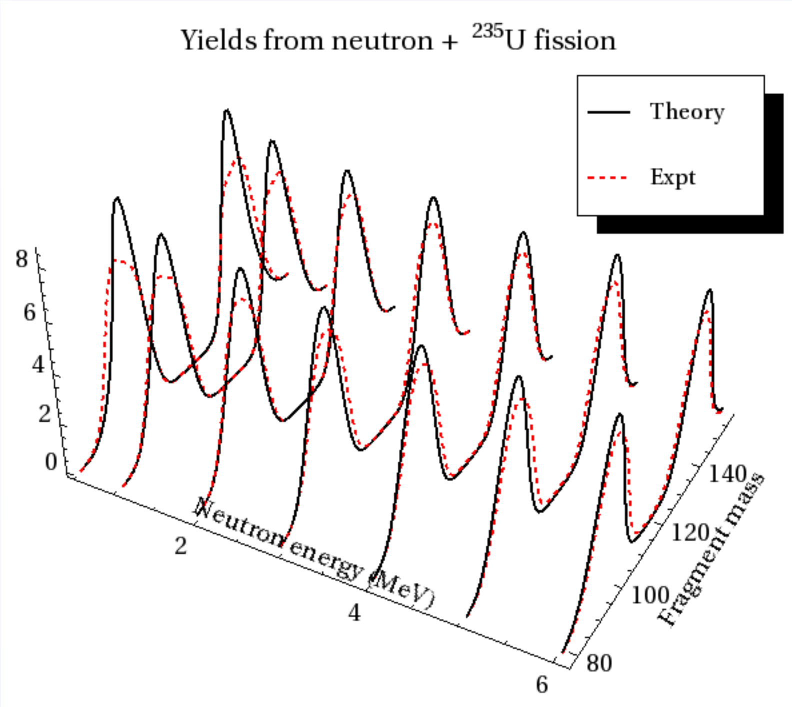
  ⇒ <u>Generator Coordinate Method</u> (GCM), Hill & Wheeler, Phys. Rev. 89, 1106 (1953)
- **Expand to 2nd order about nonlocality (q-q')**

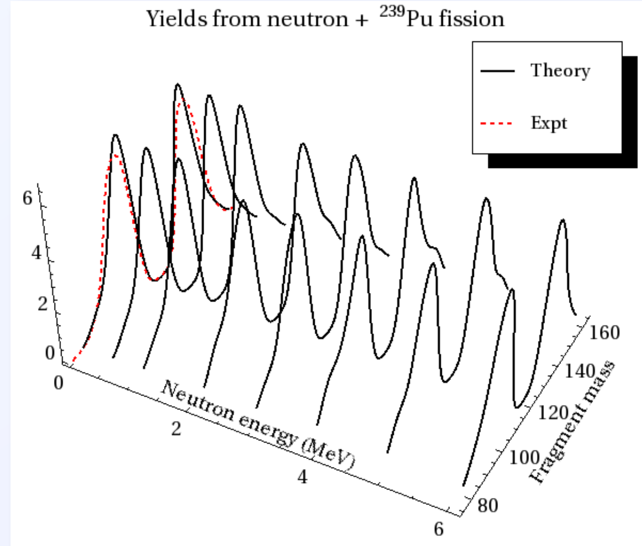
  ⇒ Time-dependent collective Schrodinger equation

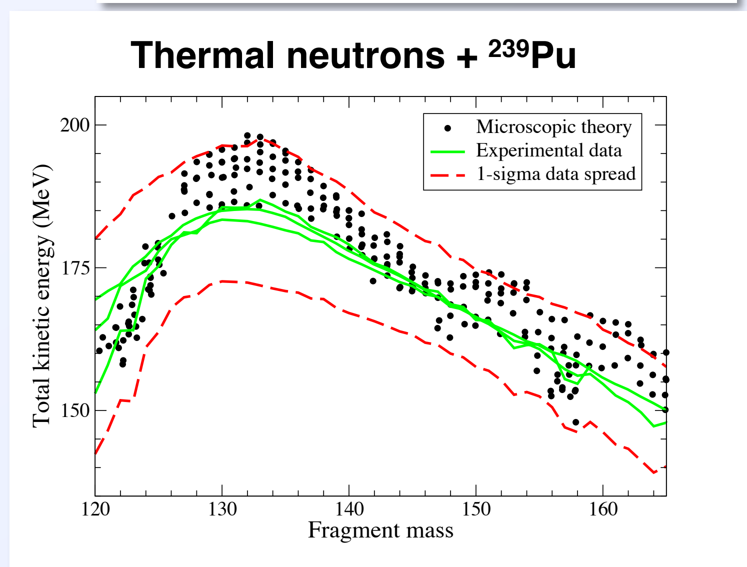


Calculations for ^{235}U(n,f) and ^{239}Pu(n,f)

Younes et al., Proc. ICFN5, p. 605 (2012)



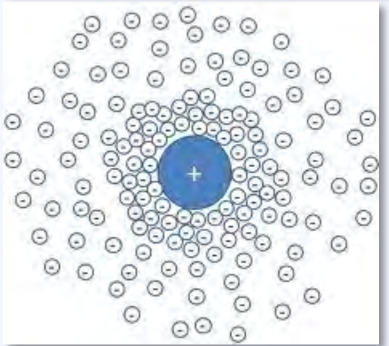




Starting from protons, neutrons, and effective interaction:
Results consistent with experiment!

Fission with electrostatically screened Coulomb interaction

HD electron gas shields protons
⇒ modified Coulomb interaction



Obtain modified Coulomb potential from screened Poisson equation with uniform free-electron gas (Fermi-Thomas approx)

$$\phi_C(r) \propto \frac{e^{-r/\lambda}}{r}$$

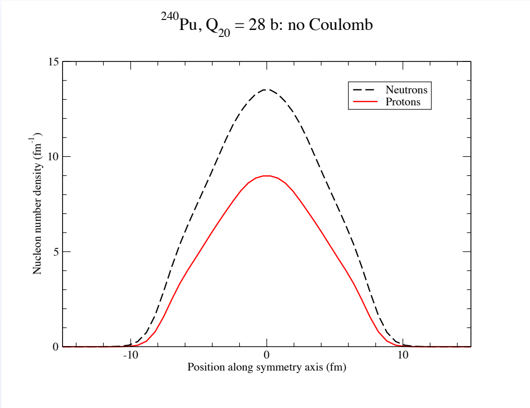
Comparison with Bürvenich et al. fission calculations:

	Bürvenich *et al.*	Proposed work
Not limited to symmetric fission	✖	✔
Calculations beyond 1st barrier	✖	✔
Effects on scission	✖	✔
Relativistic nuclei	✔	✖
Exchange terms included	✖	✔
Self-consistent pairing	✖	✔

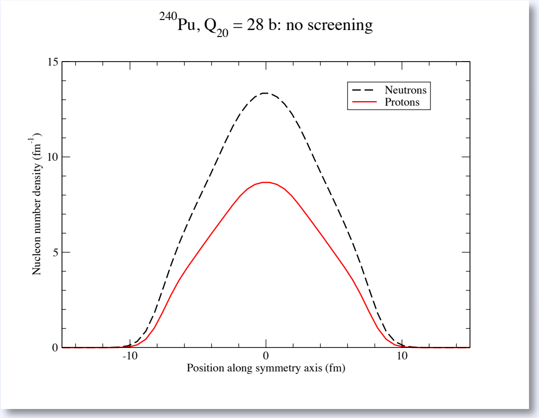
Improved scope

Improved physics

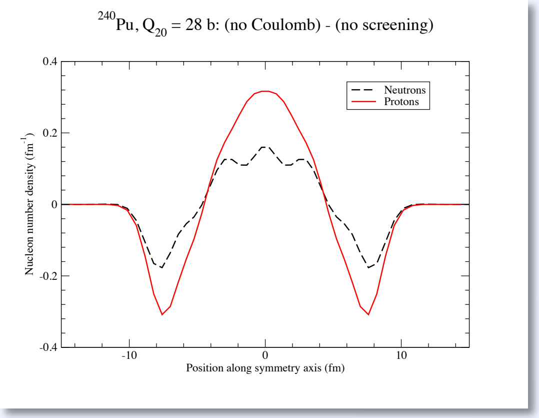
Effects of screening on nuclear densities and energies



E_{tot} = -2818.5 MeV

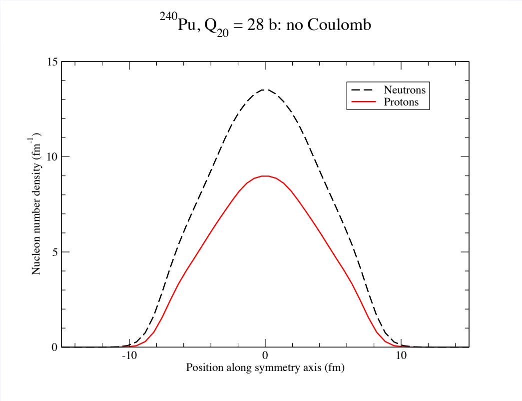


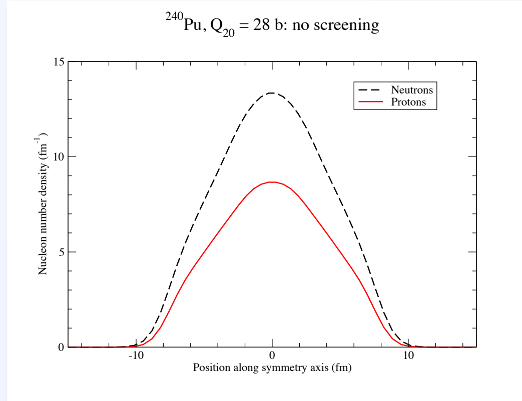
E_{tot} = -1802.9 MeV

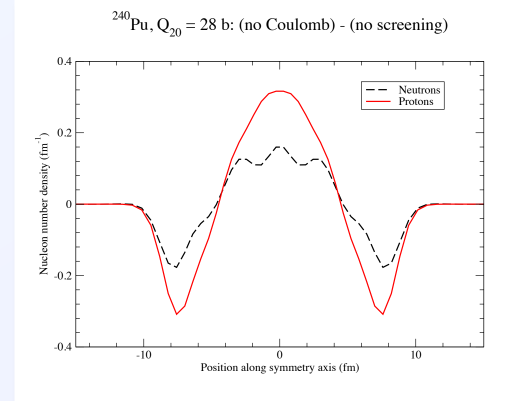


Small differences in nucleon densities lead to huge differences in energy!

Effects of screening on nuclear densities and energies







E_{tot} = -2818.5 MeV

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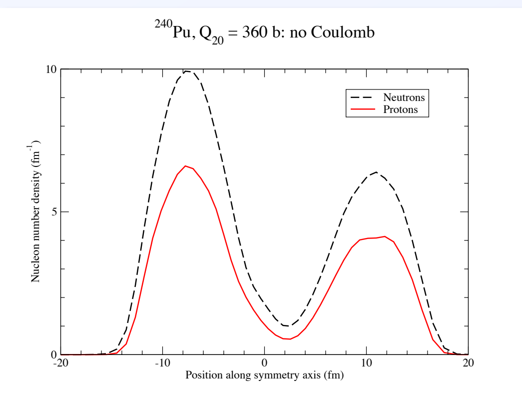
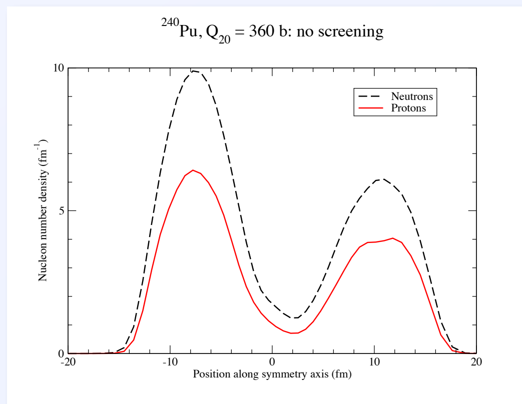
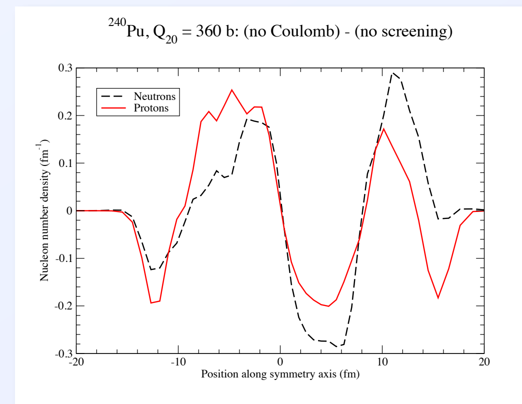




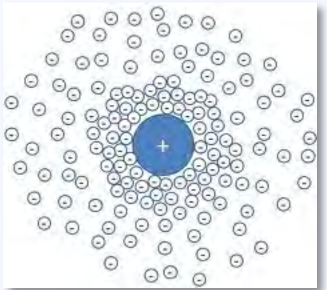


E_{tot} = -2621.0 MeV

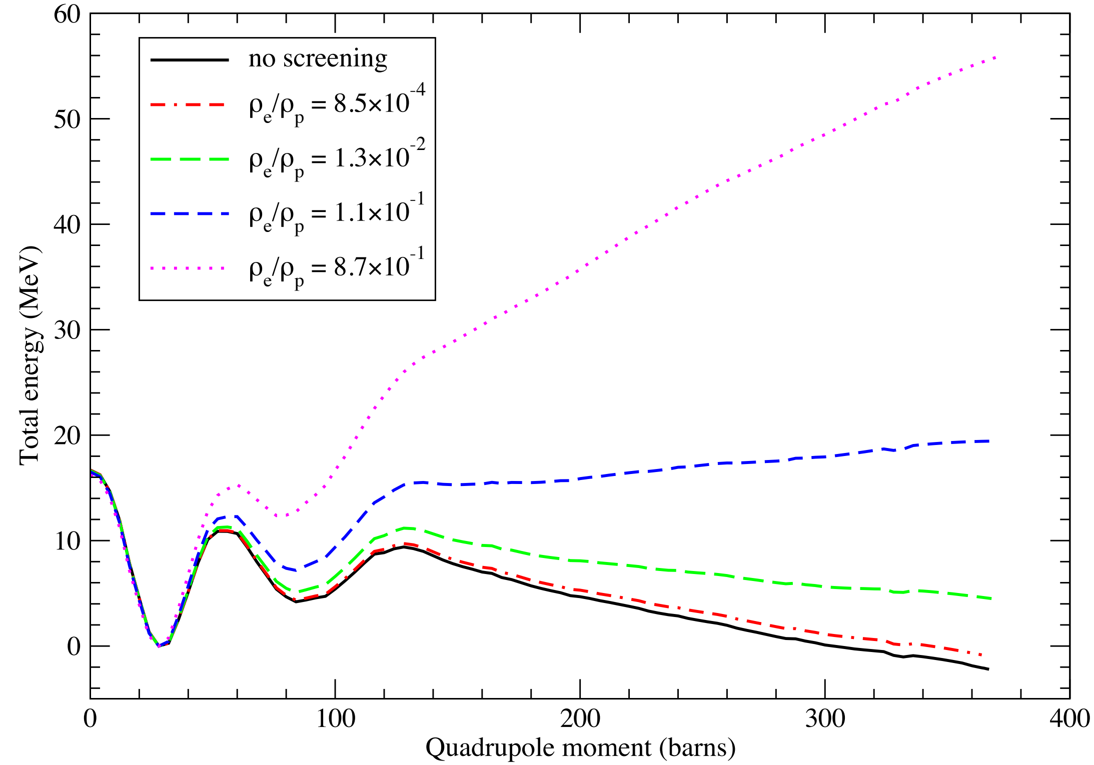
E_{tot} = -1804.8 MeV

Small differences in nucleon densities lead to huge differences in energy!

Effect of screening on ^{240}Pu energy surface

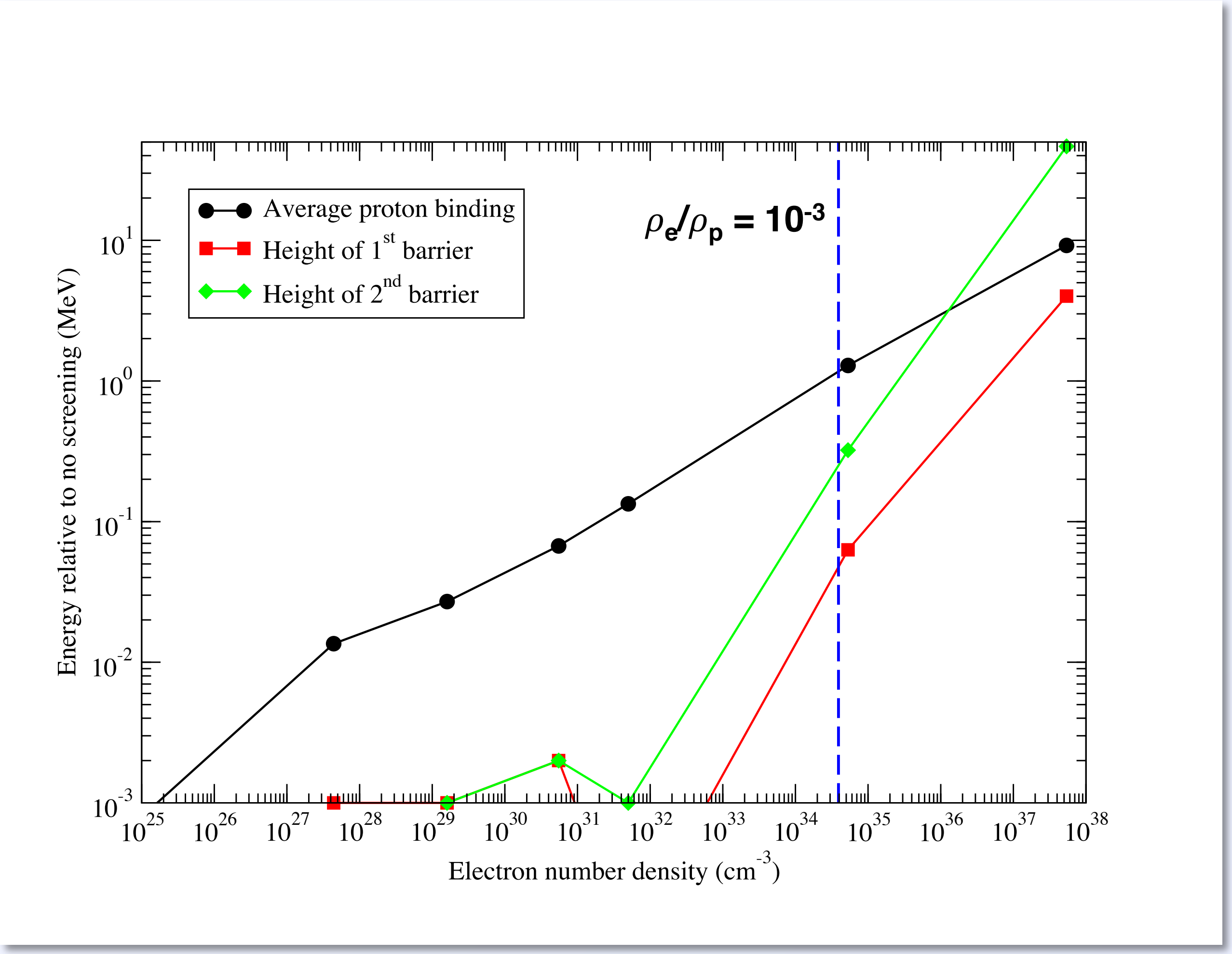


$$V_{\text{Coul}}(r) = \frac{e^{-r/\lambda}}{r}$$



- **Going all the way to scission for the 1st time**
- **Thermal fission is inhibited for $\rho_e/\rho_p \gtrsim 10^{-2}$**

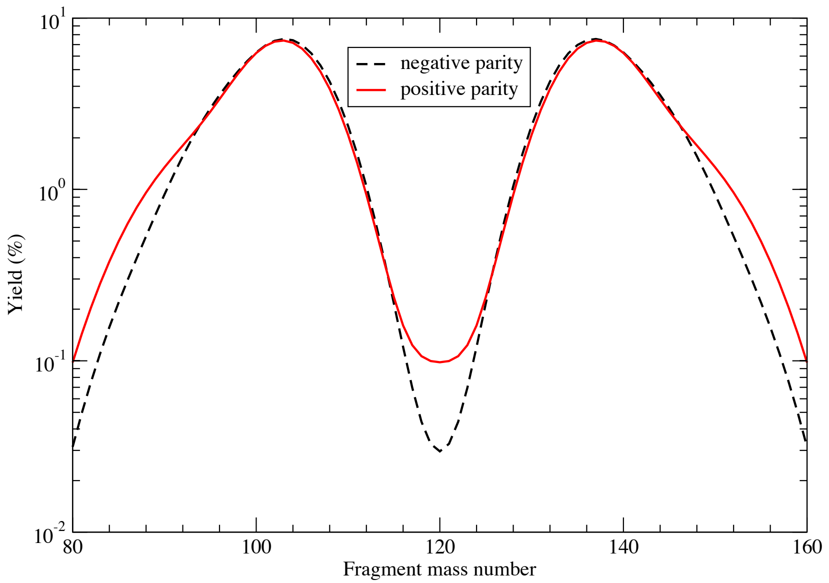
Summary of screening effects

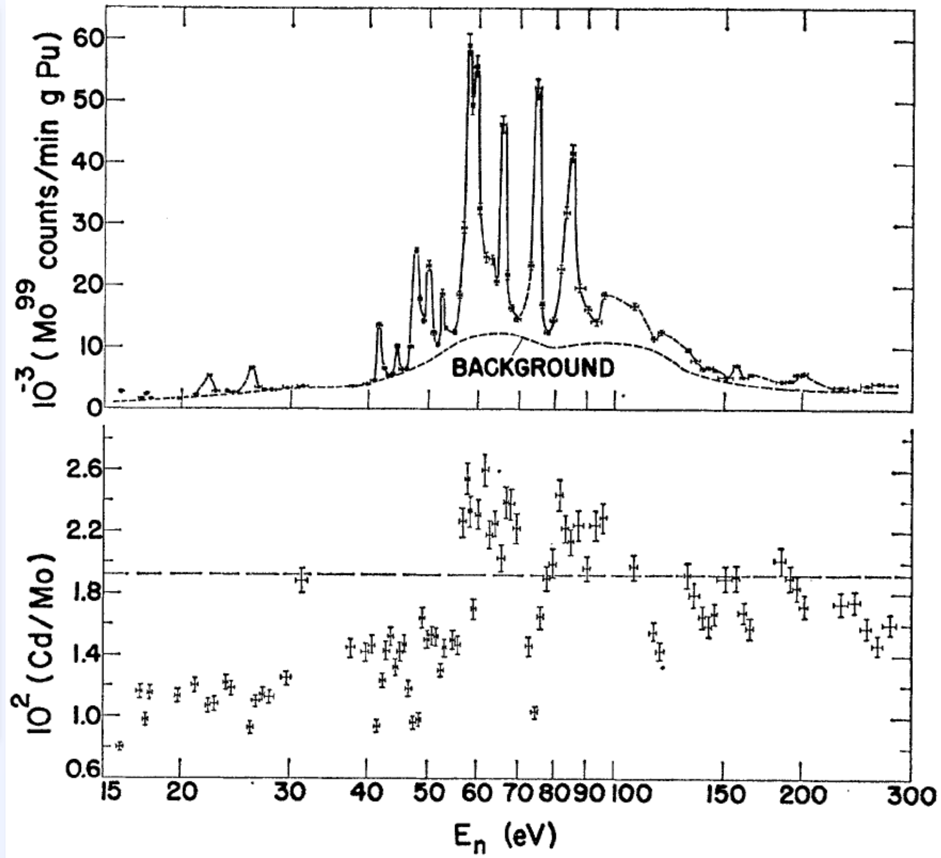


Proton binding energy is particularly sensitive, as noted by Bürvenich et al.

Effects due to large particle fluence in astrophysical plasmas

Initial states ~ 50 keV apart, different parities



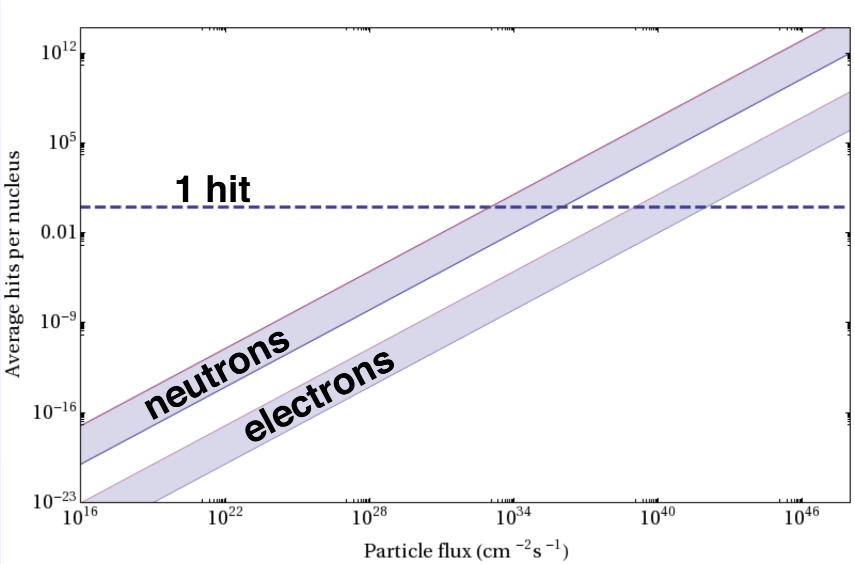


Calculations show sensitivity of fragment distributions to initial state

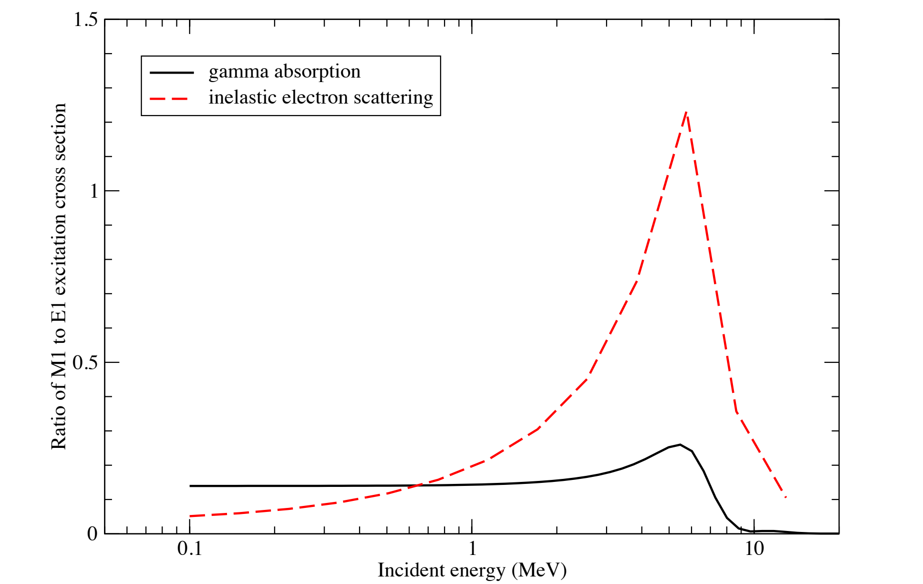
Reminiscent of resonance-fission fission experiments showing large fluctuations in peak-to-valley ratio (Cowan et al., Phys. Rev. C 144, 979 (1966))

What is the initial state in a neutron star?

Avg hits per nucleus = $\Phi\tau\sigma$
Assuming τ = ps-ns, σ = 1 μb for e^- and 1 b for n



At high enough fluxes, multiple hits before fission become likely



These hits can change the parity of the initial state

Conclusions

- Work in progress to understand the effect of modified Coulomb interaction on fission-fragment properties
  - Leveraging microscopic fission theory developed for “normal” fission
- First results show effects of screening on energy surfaces for ^{240}Pu
  - Noticeable effects for $\rho_e/\rho_p \gtrsim 10^{-2}$
- Future work:
  - So far, only considering single nucleus imbedded in electron gas
    - Next: ensemble of nuclei using Wigner-Seitz approximation
  - Extract fragment properties with screened Coulomb
  - Initial-state effects on fission-fragment properties

Acknowledgments

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  - E. Brown (MSU)